OPTICAL SWITCH

Cross-Reference to Related Application

This application claims priority of U.S. Provisional Patent Application No. 60/405,748, filed on August 22, 2002.

Background of the Invention

Field of the Invention

The invention relates to an optical switch, more particularly to an. optical switch for routing an optical signal at high speeds.

Description of the Related Art

Due to the requirement of high-speed data transmission in Internet applications, optical switches are often used in image display, data recording, data transmission and data processing. However, a conventional mechanical optical switch is expensive and has a complicated construction and low reliability. Moreover, the switching speed (e.g., 1 millisecond to 100 milliseconds) of a conventional mechanical optical switch cannot meet the demands of high-speed network communication application.

Generally, conventional mechanical switch includes a deflecting device having a movable deflector. First, two assumptions are made to simplify analysis.

1. The moment of linear displacement of the deflector is greater than, about 3.14 timer, the angular moment of the deflector when tilting.
2. The inertial mass of the deflecting device is about 3.1.4 times that of the deflector.

If the deflector is made of silicon with a density of 2.33 g/cm^3, and has a volume of 90x 90x 4μm^3, the force f and the power P required to move the deflector by a distance of 1.2 μm within a period of 40 nanoseconds are as follows:

$$f = 2\text{x}m\text{x}\ \frac{s}{t^2} = 2\text{x}7.55\text{x}10^{-8}\ \text{x}\ \frac{1.2x10^{-4}}{(4x10^{-8})^2} = 1.13\text{x}10^{4} \text{ dynes (1/9 Newton)}$$

$$P = f\,\text{x}\ -\frac{s}{t} = 1.13\text{x}10^{4}\ \text{x}\ \frac{1.2x10^{-4}}{4x10^{-8}} = 34\text{x}10^{6} \text{ watts (34 Megawatts)}$$

Both the required force f and power P are not available in conventional integrated circuits. Particularly, since it is difficult to apply a force of 1 Newton to a tiny space

smaller than a tip of a hair strand, the switching speed of the conventional mechanical optical switch is thus limited to millisecond-levels.

To solve the above problem, various techniques for mechanical optical switches, such as liquid crystal, piezoelectric, sound wave, temperature and electrostatic, lave been proposed heretofore in response to growing requirements. However, the switching speeds of mechanical optical switches using the above techniques can only be promoted to microsecond levels.

Summary of the Invention

Therefore, the object of the present invention is to provide an optical switch for routing an optical signal at high speeds.

According to the present invention, there is provided an optical switch for routing an optical signal. The optical switch comprises:

a base having a fulcrum shaft;

a deflecting member mounted movably on the base and tiltable about the fulcrum shaft so as to be adapted for deflecting the optical signal;

a plurality of elongate cantilevers disposed on the base and arranged around the deflecting member, each of the cantilevers having a hammer end portion disposed on a periphery of the deflecting member, and a coupling end portion opposite to the hammer end portion and connected to the base, each of the cantilevers being operable so as to move from a suspending position, where the cantilever is bent such that the hammer end portion is spaced apart from the deflecting member, thereby storing a restoring force in the cantilever, to a pumping position, where the hammer end portion strikes the deflecting member so as to force the deflecting member to tilt about the fulcrum shaft; and

a plurality of control units, each of which is disposed on the base, is operably associated with a corresponding one of the cantilevers, and is capable o£ controlling the corresponding one of the cantilevers to move to an appropriate one of the suspending position and the pumping position so as to enable the deflecting member to tilt to a desired direction.

Brief Description of the Drawings

Other features and advantages of the present invention will become apparent in the following detailed description of the preferred embodiments with reference to the accompanying drawings, of which:

Figure 1 is a schematic sectional view showing the first preferred embodiment of an optical switch according to the present invention;

Figure 2 is a schematic sectional view showing elongate cantilevers of the first preferred embodiment in an initial state;

Figure 3 is a schematic top view showing a deflecting member of the first preferred embodiment, viewed along line III-III of Figure 2;

Figure 4 is a fragmentary schematic sectional view showing one cantilever of the first preferred embodiment at a suspending position;

Figure 5 is a fragmentary schematic sectional view showing cane cantilever of the first preferred embodiment when moved from the suspending position to a pumping position;

Figure 6 is a schematic top view showing electromagnets of control units of the first preferred embodiment, viewed along line VI-VI of Figure 2;

Figure 7 is a timing diagram illustrating how the first preferred embodiment controls two cantilevers;

Figure 8 is a schematic sectional view showing the second preferred embodiment of an optical switch according to the present invention;

Figure 9 is a schematic top view showing a deflecting member of a third preferred embodiment of an optical switch according to the present invention;

Figure 10 is a schematic sectional view showing the deflecting member of the third preferred embodiment, taken along line X-X of Figure 9;

Figure 11 is a fragmentary schematic sectional view showing an elongate cantilever of the third preferred embodiment in an initial state;

Figure 12 is a fragmentary schematic sectional view showing one cantilever of the third preferred embodiment at a suspending position;

Figure 13 is a fragmentary schematic sectional view showing one cantilever o£ the third preferred embodiment when moved from the suspending position to a pumping position;

Figure 14 is a fragmentary schematic top view showing the fourth preferred embodiment of an optical switch according to the present invention when a sliding actuator is disposed at a holding position;

Figure 15 is a fragmentary schematic sectional view showing one cantilever of the fourth preferred embodiment at a suspending position, taken along line XV-XV of Figure 14;

Figure 16 is a fragmentary schematic view showing the sliding actuator of the fourth preferred embodiment at a releasing position; and

Figure 17 is a fragmentary schematic sectional view showing one cantilever of the fourth preferred embodiment at a pumping position, taken along line X V II - X V II of Figure 16.

Detailed Description of the Preferred Embodiment

Before the present invention is described in greater detail, it should be noted that like elements are denoted by the same reference numerals throughout the disclosure.

Referring to Figure 1, the first preferred embodiment of an optical switch 1 according to the present invention is shown. In this embodiment, the optical switch 1 is adapted to be installed in an optical router (not shown) and to be connected electrically to a drive chip (not shown) and a digital network processor chip (not shown). The optical switch 1 includes an input module 3, a plurality of output modules 4, a base 2, a deflecting member 5, a plurality of elongate cantilevers 51, and a plurality of control units 7.

The input module 3 is adapted for providing the optical signal to the deflecting member 5. In this embodiment, the input module 3 includes an input port 31 provided with an input optical fiber 32 therein. Although the input optical fiber 32 is used for transmission of the optical signal in this embodiment, an optical waveguide serving as a medium for transmitting optical signals can replace the input optical fiber 32. In this embodiment, the input optical fiber 32 has an exit end 321 having a cross-section with a diameter of 60 μm. A distance between the exit end 321 and the deflecting member 5 is less than 0.2 mm. In this embodiment, the input module 3 is disposed on one side of the deflecting member 5.

The base 2 is provided with a fulcrum shaft 22. In this embodiment, the base 2 is formed with a deflector receiving groove 20 that has a concave bottom wall 201 provided

with the fulcrum shaft 22 thereon. The fulcrum shaft 22 has a height within a range from 8 μm to 9.9 μm, and a diameter of 10 μm.

Referring to Figures 2 and 3, the deflecting member 5 is mounted movably on the base 2 and is tiltable about the fulcrum shaft 22 so as to be adapted for deflecting the optical signal from the input module 3. In this embodiment, the deflecting member 5 includes a deflector 51 disposed on the fulcrum shaft 22, and a set of suspension arms 52 arranged around the deflector 51 and interconnecting the deflector 51 and the base 2, as shown in Figure 3.

In order to reduce the dispersion in transmission of the optical signal via the input module 3, the input optical fiber 32 is chosen to be a self-focusing fiber with a low index grading rate. A self-focusing fiber is obtained with a "sech ( )" profiled refractive index distribution. The refractive index n(r) of the input optical fiber 32 can be expressed as

$$n(r) = n(0) \text{ x } \sec h(a \text{ x } r) = \frac{2xn(0)}{e^{(axr)} + e^{(axr)}}$$

where "r" is a radial distance between a test point and an axis of the input optical fiber 32, and "a" is an index grading constant. In this condition, the optical signal will be focused at a length of

$$F = \frac{n}{(2xa)} = 7.854 \text{ mm when } a = 2 \text{ per cm,}$$

regardless of the wavelength or incident angle of the optical signal as long as the optical signal is focused within a deflecting area of the deflecting member 5. Consequently, when the length of the input optical fiber 32 is equal to an integral multiple of a half period, angular divergence at the exit end 321 is

$$2n(0) \text{ x } \tan^{-1}\left(\frac{d}{f}\right) = 0.0238 \text{ Rad.} = 1.36 \text{ degree.}$$

In other words, if the distance between the deflector 51 and the exit end 321 is 6 mm, the diameter of the deflector 51 should be at least 86 μm. if the distance between the deflector 51 and each output module 4 is 8 mm, the diameter of an output optical fiber 42 of each output module 4 should be at least 200 μm.

In this embodiment, the deflector 51 has a low inertia mass, and is formed as a disk with a thickness of 4 μm and a diameter of 90 μm, which meets the above condition due to the distance between the deflector 51 and the exit end 321 being less than 6 mm. The

deflector 51 has a top surface 512 coated with a highly reflective gold film, and a bottom surface 515 formed with an O-ring shaped bump 516 at the center to fit on a tip of the fulcrum shaft 22 and a plurality of magnetic pads 514 (four in this embodiment) with an area of 300 μm^2 corresponding to a plurality of permanent magnets 21, each of which is mounted on the bottom wall 201 of the deflector receiving groove 20 in the base 2 and has a magnetic flux of 0.25 tesla, a thickness of 2 μm and an area of 600 μm^2. The deflector 51 further has a plurality of extensions 513 extending radially from a periphery of the deflector 51, as shown in Figure 3. In this embodiment, each suspension arm 52 has a serpentine configuration with a cumulative length not less than 600 μm, and a width that increases in a direction from the deflector 51 to the base 2. A maximum displacement of each suspension arm 52 at an end point is 0. 84 μm such that the strain of each suspension arm 52 is less than 0.14%. Each suspension arm 52 has a cross-section with a size of 2x2 , μm^2 fabricated through a micro -electro-mechanical process. In order to reduce unwanted oscillations of the suspension arms 52, each suspension arm 52 can be surrounded with a cushioning member (not shown) for damping purposes.

In this embodiment, four output modules 4 (only two are shown in figure 1) are disposed on another side of the deflecting member 5 opposite to said one side. Tilting of the deflecting member 5 to a desired direction results in receipt of the optical signal deflected by the deflecting member 5 by a selected one of the output modules 4. Each output module 4 includes an output port 41 provided with the output optical fiber 42 therein. The output optical fiber 42 can be similarly replaced using an optical waveguide. The output optical fiber 42 of each output module 4 has an entrance end 421 having a cross-section. with a diameter of 200μm, and has a cross-section with a diameter that is gradually reduced from 200 μm to 60 μm. A distance between the deflecting member 5 and the entrance end 421 of each output module 4 is equal to 6. 8mm (less than 8 mm) that meets the above condition.

Preferably, the input module 3 has an axis 311 that forms an angle ranging from 0° to 180° with an imaginary axis 411 parallel to the output optical fibers 42 of the output modules 4. In this embodiment, the angle is 90°. The axes 311, 411 intersect at a center of the top surface 512 of the deflector 51 . The output optical fibers 42 are evenly distributed around and respectively form a 3.55° angle with the axis 411. The 3.55° angle is coordinated with two times of the achievable tilting angle of the deflector 51.

With further reference to Figures 2, 4 and 5, the cantilevers 61 are disposed on the base 2 and are arranged around the deflecting member 5. Each cantilever 61 has a hammer end portion 63 disposed on a periphery of the deflecting member 5, and a coupling end portion 62 opposite to the hammer end portion 63 and connected to the base 2. Each cantilever 61 is operable so as to move from a suspending position, where the cantilever 61 is bent such that the hammer end portion 63 is spaced apart from the deflecting member 5, as shown in Figure 4, thereby storing a restoring force in the cantilever 61, to a pumping position, where the hammer end portion 63 strikes a corresponding one of the extensions 513 of the deflector 51 so as to force the deflector 51 to tilt about the fulcrum shaft 22, as shown in Figure 5. In this embodiment, each cantilever 61 has a length of 1.5mm and a cross-section with a size of 3200 μm^2.

With further reference to figures 4 to 6 , each control unit 7 is disposed on the base 2, is operably associated with a corresponding one of the cantilevers 61, and is capable of controlling the corresponding one of the cantilevers 61 to move to an appropriate one of the suspending position and the pumping position so as to enable the deflector 51 of the deflecting member 5 to tilt to a desired direction. In this embodiment, each control unit 7 includes a mounting member 71, an electromagnet 72, an electrostatic plate 740, and an L-shaped actuator 73. The mounting member 71, which is made of a non-magnetic material (such as silicon), is disposed on the base 2 adjacent to the corresponding one of the cantilevers 61, and has a lower mounting plate 711 formed with two mounting holes 710, and an upper mounting plate 712. The thickness of the lower mounting plate 711 is preferably 200 μm. Each o£ the lower and upper mounting plates 711, 712 has a shape that converges in a 45° angle and in a direction toward the deflector 57. so as not to block light transmission from the input module 3 to the selected output module 4. The electromagnet 72 is mounted on the mounting member 71, and has two magnet cores 721 mounted in the mounting holes 710 in the lower mounting plate 771, and a coil 722 surrounding the lower mounting plate 711, as shown in Figure 6. The actuator 73 leas an intermediate pivot portion 731 connected pivotally to the mounting member 71 and pivotable about a pivot axis (A) transverse to the fulcrum shaft 22, an elongate hooking portion 732 connected to the intermediate pivot portion 731 and extending through a through hole 713 in the magnet core 721 and a through hole 613 in the corresponding one of the cantilevers 61, and an electrostatically-attractive interacting portion 733 connected to the intermediate pivot

portion 731 and transverse to the hooking portion 732. The electrostatic plate 740 is mounted on the upper mounting plate 712 and is disposed above the interacting portion 733 of the actuator 7. In this embodiment, the cantilevers 61 are made of magnetically-attractive. The electromagnet 72 is operable in one of an energized state and a de-energized state. The electromagnet 72 attracts the hammer end portion 63 when in the energized state so as to enable the actuator 73 to pivot about the pivot axis (A) such that the hooking portion 732 moves and holds the lifted hammer end portion 63 of the corresponding one of the cantilevers 61 to dispose the corresponding one of the cantilevers 61 in the suspending position, as shown in Figure 4. The electromagnet 72 pre-releases the hammer end portion 63 of the corresponding cantilever 61 when in the de-energized state while the electrostatic plate 740 is operable to attract the interacting portion 733 so as to enable the actuator 73 to pivot about the pivot axis (A) such that the hooking portion 732 permits movement of the hammer end portion 63 of the corresponding one of the cantilevers 61 to dispose the corresponding one of the cantilevers 61 in the pumping position by virtue of the restoring force in the corresponding one of the cantilevers 61. It is noted that, if each cantilever 61 is magnetically attractive and has an area large enough to be attracted by the electromagnet 72 so as to dispose the cantilever 61 in the suspending position, the actuator 73 can be omitted.

The optical switch 1 of the present invention can be applied to a communication system with 300 channels, such as in the DWDM (Dense Wavelength Divided multiplexing) mode operations, for transmission of 128-bit data packets at a speed of 40 Gbps (Giga bits per second). Referring to Figure 7, the cantilevers 61 are disposed in the suspending position at initial time t_o when the cantilevers 61 are in the energized state. A first data packet can be transmitted within a period from t_o to t_1 (about 0.96 μs). The control unit 7 controls the electrostatic plate 740 corresponding to one cantilever 61 to release the interacting portion 733 of the actuator 73 associated with said one cantilever 61 at t_1. As such, a second data packet can be transmitted to a desired one of the output modules 42 within a period from t_2 to t_3 (about 0.96 μs) , and the time period from t_1 to t_2 is about 10ns. Thereafter, the control unit 7 controls the electrostatic plate 740 corresponding to another cantilever 61 to release the interacting portion 733 of the actuator 73 associated with said another cantilever 61 at t_3. As such, a third data packet can be transmitted to a desired one of the output modules 42 within a period from t_4 to is (about 0.96 μs), the time period from t_3 to t_4 being about 10ons. It is noted that a third data packet should be

transmitted to a desired one of the output modules 42 at t_4. It takes about 1 μs to move the cantilever 61 from the pumping position to the suspending position. The period from t_2 to T_s is 1.93 μs Therefore, the optical switch 1 of this invention can be switched in sufficient time during data transmission.

Figure 8 illustrates the second preferred embodiment of an optical switch according to this invention, which is a modification of the first preferred embodiment Unlike the embodiment of Figure 1, the input module 3' is substantially aligned with the fulcrum shaft 22 . The output modules 4' are disposed around the input module 3'.

Figure 9 to 11 illustrate the third preferred embodiment of an optical switch according to this invention, which is a modification of the first preferred embodiment. Unlike the previous embodiment, the deflecting member 5' includes a deflector 51' having a deflecting side 512' and a mounting side 515' opposite to the deflecting side 512'. The deflector 51' is formed with a plurality of projections 522 extending radially from a periphery of the deflector 51', as shown in Figure 9. The base 2' .is formed with a deflector receiving recess 24. The fulcrum shaft 22 is disposed in the deflector receiving recess 24. The deflector receiving recess 24 is confined by a confining wall 25 that extends parallel to the fulcrum shaft 22. The confining wall 25 is formed with a plurality of guiding grooves 251 corresponding to the projections 522 on the deflector 51' such that the projections 522 are positioned movably and respectively well within the guiding grooves 251 when the mounting side 515' of the deflector 51' is disposed on the fulcrum shaft 22 in the deflector receiving recess 24, as shown in Figure 10. The deflecting member 5' further includes a set of magnetic plates 514' mounted on the mounting side 515' of the deflector 51'. The base 21 is further provided with a set of permanent magnet blocks 21' in the recess 24 and corresponding to the magnetic plates 514' for stabilizing the deflector 51' when one of the cantilevers 61 strikes the deflector 51'.

Ref erring to Figure 11, each control unit 7' includes a driving member 71', a first electromagnet member 75, a second electromagnet member 76,and an L-shaped actuator 73'.

The driving member 71' is connected pivotally to the base 21 and is disposed on the base 2' adjacent to the corresponding one of the cantilevers 61. The driving member 71' has a first intermediate pivot portion 714 connected pivotally to the base 2' and pivotable about a first pivot axis (B) transverse to the fulcrum shaft 22, a driving end portion 715 connected

to the first intermediate pivot portion 714 and disposed above the corresponding one of the cantilevers 61 and adjacent to the deflecting member 5', and a magnetically-attractive end portion 716 opposite to the driving end portion 715 and connected to the first intermediate pivot portion 714. In this embodiment, the magnetically-attractive end portion 716 is formed with a magnetic plate 717.

The first electromagnet member 75 is mounted on the base 2' and is disposed adjacent to and below the magnetic plate 717 on the end portion 716 of the driving member 71'.

The second electromagnet member 76 is mounted on the driving end portion 715 of the driving member 71'.

The L-shaped actuator 73' has a second intermediate pivot portion 731' connected pivotally to the driving end portion 715 of the driving member 71' and pivotable about a second pivot axis (C) transverse to the fulcrum shaft 22 and parallel to the first pivot axis (B), an elongate hooking portion 732' connected to the second intermediate pivot portion 731', and extending through a through hole 7151 in the driving end portion 715 and a through hole 613 in the corresponding one of the cantilevers 61, and a magnetically-attractive interacting portion 733' connected to the second intermediate pivot portion 731' and disposed adjacent to the second electromagnet member 76.

The first electromagnet member 75 is energized to attract the magnetically-attractive end portion 716 of the driving member 71 , so as to enable the driving member 71' to pivot about the first pivot axis (B) such that the hooking portion 732' of the actuator 73' moves with the driving end portion 715 of the driving member 71' so as to hook the hammer end portion 63 of the corresponding one of the cantilevers 61 when the second electromagnet member 76 is energized to attract the interacting portion 733' of the actuator 73' in order to dispose the corresponding one of the cantilevers 61 in the suspending position, as shown in Figure 12.

The second electromagnet member 76 is energized (see Figure 12), and is de-energized to release the interacting portion 733' of the actuator 73' and enable pivoting movement of the actuator 73' such that the hooking portion 732' of the actuator 73' permits movement of the hammer end portion 63 of the corresponding one of the cantilevers 61 to dispose the corresponding one of the cantilevers 61 in the pumping position by virtue of the restoring force of the corresponding one of the cantilevers 61, as shown in Figure 13.

Figure 14 to 17 illustrate the fourth preferred embodiment of an optical switch according to this invention, which is a modification of the first preferred embodiment. Unlike the previous embodiments, each control unit 8 includes a mounting member 81, a first electromagnet member 82, a magnetically-attractive working plate 83, a second electromagnet member 84, and a sliding actuator 85.

The mounting member 81 is disposed on the base 2' adjacent to the corresponding one of the cantilevers 61'.

The first electromagnet member 82 is mounted on the mounting member 81.

The working plate 83 is disposed below the first electromagnet member 82, and has a connecting end 831 connected to the mounting member 81, and a driving end 832 opposite to the connecting end 831, and disposed below the hammer end portion 63' of the corresponding one of the cantilevers 61'.

The second electromagnet member 84 is mounted on the mounting member 81, and is disposed adjacent to the coupling end portion 62' of the corresponding one of the cantilevers 61'.

The actuator 85 is disposed slidably between the base 2' and the corresponding one of the cantilevers 61', and has a magnetically-attractive interacting portion 851 disposed adjacent to the second electromagnet member 84, and an elongate actuating portion 852 connected to the interacting portion 851 and disposed directly underneath the corresponding one of the cantilevers 61'. The actuating portion 852 is formed with an upwardly extending actuating projection 853. The corresponding one of' the cantilevers 61` is formed with a receiving groove 611 corresponding to the actuating projection 853. In this embodiment, the actuating portion 852 has a bottom surface 8521 formed with an elongate guiding groove 8522. The base 2' has a top surface formed with an elongate guiding rib 23 that engages slidably the guiding groove 8522, as shown in figures 15 and 17.

The first electromagnet member 82 is operable in one of an energized state and a de-energized state. The first electromagnet member 82 attracts the working plate 83 when in the energized state to move upwardly the hammer end portion 63' of the corresponding one of the cantilevers 61' so as to dispose the corresponding one of the cantilevers 61' in the suspending position.

The second electromagnet member 84 is operable so as to drive the actuator 85 to move from a holding position, where the actuating projection 853 holds the corresponding

one of the cantilevers 61' in the suspending position when the first electromagnet 82 is operated from the energized state to the de-energized state, as shown in Figure 24, to a releasing position, where the actuating projection 853 extends into the receiving groove 611 in the corresponding one of the cantilevers 61' so as to permit movement of the hammer end portion 53' of the corresponding one of the cantilevers 61' to dispose the corresponding one of the cantilevers 61' in the pumping position by virtue of the restoring force in the corresponding one of the cantilevers 61', as shown in Figure 17.

In the above embodiments, the optical switch of this invention can also be fabricated via a bulk micro machining process, a surface micro machining process, a precision micro machining process, an electro-discharge micro machining process, a laser micro machining process, etc. Furthermore, since the cantilevers 61 are arranged around the periphery of the deflector 51, the optical switch of this invention provides a relatively large space for various arrangements of the cantilevers 61 using conventional low-cost technology.

To sum up, the optical switch of this invention utilizes the period for transmitting the optical signal to the input module to dispose the cantilever 61 in the suspending position. Then, the cantilever 61 can be controlled so as to be moved from the suspending position to the pumping position within a period of nanosecond-level such that the optical switch can be switched at a relatively high speed.

While the present invention has been described in connection with what is considered the most practical and preferred embodiments, it is understood that this invention is not limited to the disclosed embodiments but is intended to cover various arrangements included within the spirit and scope of the broadest interpretation so as to encompass all such modifications and equivalent arrangements.